APPENDIX 8-10

RESERVOIR SEEPAGE ANALYSIS
TECHNICAL MEMORANDUM

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BLACK & VEATCH

TECHNICAL MEMORANDUM

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EAA Reservoir A-1	B&V File: C-1.3
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Task 16.19 Reservoir Seepage Analysis Technical Memorandum

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From: Dominic Molyneux

1. INTRODUCTION

1.1 Background

In October 2003, the South Florida Water Management District (District) decided to pursue a "Dual Track" for the Everglades Agricultural Area (EAA) Reservoir project. While the multi-agency Project Delivery Team, lead by the Corps of Engineers, continues to develop the Project Implementation Report, the District is proceeding with the design of a reservoir (designated EAA Reservoir A-1 Project) located on land acquired through the Talisman exchange in the Everglades Agricultural Area.

The EAA Reservoir A-1 Project is located in Palm Beach County with an anticipated total storage capacity of approximately 190,000 acre-feet and a maximum storage depth of water to be approximately 12 feet.

The purpose of the Project as defined in the CERP is to capture EAA Basin runoff and releases from Lake Okeechobee. The facilities will be designed to improve the timing of environmental water supply deliveries to STA 3/4 and the WCA's, reduce Lake Okeechobee regulatory releases to the estuaries, meet supplemental agricultural irrigation demands, and increase flood protection within the EAA.

To proceed with implementation of the EAA reservoir, the District selected Black & Veatch from the General Engineering Services Contracts, Full Services to complete the 30% design services for the EAA Reservoir A-1 and associated pump stations.

This Technical Memorandum follows a Test Cell Program which was carried out to provide a basis for key design criteria for the EAA Reservoir A-1 project. Other results from the Program are reported in Reservoir Seepage Analysis Technical Memorandum, Test Cell Construction and Seepage Monitoring Report, Reservoir Configuration Memorandum, and the Embankment Technical Memorandum. These Technical Memoranda have been developed in parallel to this stage, and this Memorandum does not describe or include the recommendations from the others.

The next stage of the design process will bring the different facets together in a single recommended design solution.

It is not traditional to store water as deep as 12' above ground level in the Everglades area. Seepage control or mitigation (prevention) is the primary design issue to be considered. A seepage cutoff wall is a traditional seepage control measure for reservoir sites containing subsurface stratification with high permeability rates. The perimeter length of embankment at Reservoir A-1 and potential depth required to achieve an effective cutoff could make a seepage cutoff wall a significant cost factor to be considered in the reservoir design. The results of the previous modeling presented in the Report for Conceptual Levee High Alternatives (CLHA Report) indicate that a slurry wall could be effective in reducing seepage losses from the reservoir and the resulting seepage collected and available to be reclaimed or recycled into the reservoir is reduced.

Recoverable seepage refers to the amount of water which is collected in the seepage canals and must be re-pumped into the reservoir. Based on seepage amounts listed in the CLHA Report, a cutoff wall under the embankment would reduce overall seepage and could eliminate the need for re-pumping up to 55 cfs at the peak condition. The confidence level expressed in the subject report was very low as demonstrated by the statement that permeabilities could vary by a factor of 10 to 100 or more. Therefore, in order to demonstrate an order of magnitude savings from installing a cutoff, it was assumed that installing a cutoff would eliminate the need for pumping the 55 cfs on a continuous basis. This resulted in an estimated present worth of $12 million in potential savings.

Subsurface data presented in the CLHA Report indicates variability in the number, thickness, and sequence of individual substrata across the reservoir site. The evaluation of seepage potential and the effectiveness of control measures using typical test well analysis procedures can be misleading unless the variability in site conditions is appropriately considered. The description of subsurface conditions includes three geologic units within the upper 110 feet of the stratigraphy below the surface. The two units below the surface peat contain 3 or more defined stratum, each characterized by depth, thickness, and hydraulic conductivity. The defined strata are not considered to be continuous as portrayed in the idealized stratigraphic model. The strata are considered to be lenticular in nature as a result of the past depositional and erosional environment. Definition of the appropriate subsurface model to evaluate the seepage potential from the reservoir is significantly complicated by the variability in the subsurface stratification.

1.2 Objectives

One objective of the test cell program was to obtain the data required for the development of a model that is not dependent on the specific hydrogeological characteristics of a single unit in order to evaluate the reservoir seepage potential effectively. The test cell program was designed to obtain hydraulic conductivity data or the average mass hydraulic conductivity value of a single geologic unit thereby reducing the variables to be considered to unit thickness, cutoff depth, and distance and depth of a seepage collection canal, if required.

The hydraulic conductivity values and seepage control measures considered appropriate as a result of the test cell program will be input into the reservoir seepage and mass balance model. Additional hydraulic modeling using measured flow into the seepage collection canal will be required to determine the proper sizing of the pump stations located on the collection canal.

The objective of this Reservoir Seepage Technical Memo is to report on calibration of permeabilities for use in the seepage model using the information obtained from the test cell monitoring program and the computer software SEEP/W.

1.3 Related further work

Since its first issue on May 31, 2005, the work presented in this Technical Memorandum has been extended with further calibration using the MODFLOW three dimensional, finite element, computer software as reported in the Groundwater Model Technical Memorandum. During the design stage both models will be used: SEEP/W will be used to investigate effects local to the dam such as hydraulic exit gradient and the impacts of cut-off depth; MODFLOW uses a coarser mesh and will be used for the wider area impacts such as total reservoir losses and groundwater level effects. The hydraulic conductivity values derived from the model calibration presented in the Groundwater Model Technical Memorandum will be the basis for further work to perform seepage analysis of the A-1 Reservoir.

2. GEOLOGICAL CONDITIONS

An appreciation of the geological setting is of prime importance to successfully modeling of the groundwater regime at site.

2.1 Near Surface Conditions

The land surface at the test cell site and the entire site of the EAA Reservoir is covered with 1 to 2 feet of black, highly organic, fine grained soil known locally as muck or peat. The muck is often underlain by several inches to 2 feet of calcareous clay locally called marl. The muck and marl constitute the local soil in the EAA. The peat and marl were scraped from the area inside the test cells and from underneath the embankments.

2.2 Regional Hydrogeology

The Project is located south of Lake Okeechobee within the Everglades physiographic subdivision of the Southern Zone (White, 1970). The Everglades is generally a flat, geologic depression between the Immokalee Rise and Big Cypress Spur physiographic subdivisions on the west, and the Atlantic Coastal Ridge physiographic subdivision on the east. The Everglades extends southward from Lake Okeechobee to Florida Bay with elevations near sea level. With the exception of the EAA, the Everglades landscape consists primarily of sawgrass marsh with hammocks of willow, myrtle and bay trees.

The United States Department of Agriculture, Natural Resources Conservation Service (NRCS and formerly known as the Soil Conservation Service) published a soil survey for the Palm Beach County area in the mid 1970s (McCollum et al., 1978). Seven primary soil types were identified in the EAA, including the Torry muck, Terra Ceia muck, Pahokee muck, Lauderhill muck, Dania muck, Okeelanta muck, and Okeechobee muck. The soils at the EAA Reservoir A-1 Project include the Pahokee muck (primarily in the southern portion of the site) and Lauderhill muck (primarily in the northern portion of the site). Based on geotechnical borings at the EAA Reservoir A-1 Project, the muck ranges in thickness from less than one ft to approximately five ft. According to the NRCS, the soils located beneath the former Talisman Sugar Corporation processing facility are classified as Urban land. Urban land soils are those which have been disturbed due to development.

In general, the surface and near surface geology of the region is complex and ranges from unconsolidated, variably calcareous and fossiliferous quartz sands to well indurated, sandy, fossiliferous fresh and marine limestones (Scott, 2001). These sediments are Pleistocene to recent in age, and blanket most of Palm Beach County except for the Atlantic Coastal Ridge sediments on the east coast. The regional geologic units are generally referred to, in descending order, as the Lake Flirt Marl, Fort Thompson Formation, and Caloosahatchee Formation. The total thickness of these units can range from 50 to nearly 200 ft in the region. It should be noted that Scott (2001) has proposed grouping the Fort Thompson Formation and Caloosahatchee Formation into a single lithostratigraphic entity, the Okeechobee formation (informal). Scott's proposal is based on the lack of identifiable biostratigraphic zones that warrant distinguishing the Fort Thompson Formation from the Caloosahatchee Formation.

The Pliocene-age Tamiami Formation underlies the Caloosahatchee Formation. The Tamiami Formation contains a wide range of mixed carbonate-siliciclastic lithologies and associated faunas (Missimer, 1992). The Tamiami Formation in the area of the Project is approximately 100 ft thick. The upper portion of the Tamiami Formation and overlying geologic units comprise the surficial aquifer system in Palm Beach County.

The Miocene-age Hawthorn Group underlies the Tamiami Formation. The Hawthorn Group consists of an interbedded sequence of widely varying lithologies and components that includes limestone, dolomite, dolosilt, shell, quartz sand, clay, phosphate grains and mixtures of these materials (Reese and Memberg, 2000). The characteristics that distinguish the Hawthorn Group from underlying units are its high and variable siliciclastic and phosphatic content; its color, which can be green, olive-gray, or light gray; and its gamma-ray log response. According to Scott (1988), the Hawthorn Group is approximately 700 ft thick in the region. The Hawthorn Group sediments retard the exchange of groundwater between the overlying surficial aquifer system and the underlying Eocene-age carbonates of the Florida aquifer system, and is hydrogeologically referred to as the intermediate confining unit.

The Eocene-age carbonates underlying the Hawthorn Group include, in descending order, the Ocala Limestone, Avon Park Formation, and Oldsmar Formation. The overlying Oligocene-age Suwannee Limestone is thin to discontinuous in the EAA region, and likely not present in the east half of Palm Beach County (Miller, 1986). The cumulative thickness of the Eocene-age carbonates in the region is approximately 2,500 ft (Miller, 1986). See Figure 1.

2.3 Subsurface Conditions

Numerous soil borings completed from 50 to 100 ft below ground surface were completed at the EAA Reservoir A-1 Project test cell site prior to the Test Cell Program in December 2004 and during the test cell construction in early 2005. The borings generally penetrated through approximately 0.5 to 2 ft of surficial peat/muck and marl, then through 22 to 26 ft of primarily carbonate sand and limestone, and then into primarily shelly quartz sand with sparse limestone to their completed depths. The marl beneath the peat and muck is known by some authors as the Lake Flirt Marl (Reese and Cunningham, 2000; Harvey, et. al., 2002), but is undifferentiated from the peat and muck layer for this report. The upper carbonate sand and limestone constitutes the Fort Thompson Formation at the site. Below this, the shelly sand and sparse limestone constitutes the Caloosahatchee Formation and possibly part of the Tamiami Formation.

The top of the Fort Thompson Formation consists of a hard limestone layer about 4.5 to 5 ft thick, which is locally called caprock. The caprock is generally white, light gray, tan or yellowish brown.

The caprock is underlain by a silty carbonate sand extending to about 23.5 to 24.5 ft deep, where another hard limestone layer 1.5 to 3 ft thick is encountered. A thinner, hard limestone layer about 0.5 to 1 ft thick is often encountered at around 16 to 17 ft deep. The sand and lower limestone layers are generally white to very pale brown. Laboratory testing of the sand sampled in the borings averaged 84.2% calcite content with an average of 22% passing the #200 sieve in gradation tests. Visual inspection of the sand samples from the borings reveals that they include shell fragments, and tend to be angular and platy.

The limestone layers in the Fort Thompson appeared to be the primary sources of groundwater seepage into the site excavations, the SCCs and the Borrow Area. Water could be seen streaming from the bottom of each of the three limestone layers in the dewatered excavations. They are all jointed, and the caprock contains solution cavities including local areas of anastomosing channels especially near the top and single channels up to several inches in diameter that penetrate the full thickness. The solution channels in the caprock locally contain soil including the peat and marl.

All the Fort Thompson Formation limestone layers exposed in core or in excavations at the reservoir site are very fossiliferous. The sand exposed in the seepage collection canals (SCCs) and dewatering sumps was abundantly fossiliferous with gastropods, pelecypods, corals, and echinoderms.

The top of the Caloosahatchee Formation is composed of fine grained, subrounded, shelly quartz sand that is mixed with shelly carbonate sand similar to that in the Fort Thompson Formation. The Caloosahatchee Formation at the reservoir site is 30 to 60 ft thick; however, the interface between this formation and the underlying Tamiami Formation is difficult to define. The proportions of carbonate to quartz sand vary. Laboratory testing on the sampled sand indicated an average calcite content of 40.1%, and an average 12.1% of material passing the #200 sieve. The primary color of the geologic material in the Caloosahatchee Formation is light greenish gray.

Other geologic information may indicate that the Caloosahatchee Formation is not present at the EAA Reservoir A-1 Project. For instance, recent geological work (Reese and Cunningham, 2000) has redefined the stratigraphy of the area. Presently, the Tamiami Formation has several recognized named and unnamed geologic members including the Ochopee Limestone Member and the Pinecrest Sand Member. Both Tamiami Formation members contain sandy strata, but the Pinecrest Sand Member is principally shelly, fine grained, quartz sand. The sands in the Caloosahatchee and Tamiami Formations are generally differentiated based on the fossil assemblages observed in outcrops, but key indicator fossils are typically not recovered in borings (personal communication from Thomas M. Scott, Ph.D., P.G., and Assistant State Geologist). Therefore, interpretation of the contact between the Caloosahatchee Formation and Tamiami Formation at the EAA Reservoir A-1 Project is not possible.

Fish (1987) proposes the ranges of hydraulic conductivities for materials in the surficial aquifer system as shown in Table 1. Fish's work focused on Broward County to the south of the EAA Reservoir site, but it is likely that the variability of the materials is similar in both areas. The table shows an enormous range of conductivities possible Fort Thompson and Tamiami Formations.

This variability and horizontal structuring is further illustrated in the cross section below (Figure 2) which is drawn from south (F) to north (F') close to the general line of US 27. The north end of the cross section is on the Palm Beach to Broward County lines which is south of the EAA Reservoir site.

3. OBSERVATIONS FROM TEST CELL CONSTRUCTION

The test cell configuration and instrumentation plan are provided on the drawings (Sheets 2, 3, 4, and 9 of 11) for the Temporary Test Cell construction in Appendix 8-24.

3.1 Seepage through the Embankment

3.1.1 Seepage Collection System

3.1.1.1 Test Cell 1

Test Cell 1 was designed with an inclined filter and drain system on the downstream side of the core and along the foundation to the toe of the dam. A berm was constructed around the downstream side of the embankment to collect the water in the drainage system and direct it to sumps where it could be pumped away and the total flow measured. In the event, much higher flows occurred than the system had been designed to accommodate, and the toe berm had to be broken open to allow the water to escape without increasing water pressure within the embankment. Even with the slots cut in the toe berm, water levels were above caprock level within the embankment, approximately 2 feet in places.

Vibrating wire piezometers were installed in the core of the test cell embankment. During filling there was little response to reservoir water level. The inference drawn from this observation is that the seepage that was observed at the toe of the embankment was due to water flowing in the cap rock underneath the core contact and rising into the drainage system. Flow through the core was probably so small that it was not measurable in comparison.

3.1.1.2 Test Cell 2

Test Cell 2 was designed with a perforated plastic pipe toe drain system. The system drained to two sumps which were then intended to be pumped down and the flows measured.

In the field, the northern sump and pipe system remained dry for the duration of the site trials.

Some flow was observed in the southern sump. However, the flow did not appear to be related to test cell level and on occasions when the sump pump broke down, the water level in the sump only rose to canal level. Observations on site suggest that virtually no water was entering the system from upstream and the water was simply being re-circulated from the canal downstream. The cap rock level on which the sump and drain were founded was below the seepage canal level.

3.2 Vibrating Wire Piezometers

Vibrating wire piezometers were installed within the core of the embankment. These instruments registered excess pore pressures, caused by construction, which dissipated with time. The instruments showed little response to filling of the test cells and it is unlikely that the select fill material reached equilibrium in terms of seepage. This demonstrates that the fill was relatively impermeable and an effective water barrier.

3.3 Foundation Seepage

3.3.1 Test Cell 1

Extensive seepage through the foundation was observed at the outside toe of slope of the embankment at Test Cell No. 1. The peat soil layer was removed between the embankment and seepage canal at both test cells. At test Cell No. 1, the flat bench area between the embankment and the seepage collection canal was wet and water stood in the low areas in the caprock. Boils were observed from the caprock surface near the embankment toe and in some cases as far as 15' to 20' from the toe of embankment slope. Water from within the caprock, or just under it, rose above the outer casing of piezometer PZ1E2C. This was about 1.5 ft above top of caprock. These observations indicate that the caprock confined the hydraulic pressure in shallow layers except where worm holes allowed relief. In these areas of relief muck and fine particles were ejected from within the caprock in the form of boils.

The seepage observed at the outside toe of embankment slope of Test Cell No. 1 was reduced when the water in seepage canal was lowered from approximately 7 ft El. to El. 2.0 ft. However, water was still observed issuing from the voids in the caprock near the outside embankment toe of slope. Water in an old open drill hole in the caprock on the south side of the test cell flowed over when the test cell was held at 12 ft depth and the seepage canal was at normal background level. When the seepage canal was pumped down to El.2.0 ft the water level in this hole dropped to about 1.5 ft below caprock level.

The seepage collection canal was observed during the trials. When the test cell was at 12ft depth and seepage canal at background level, there was one area on the north side of the canal where slight turbulence could be detected in the water surface, under still conditions. This indicated a concentrated flow path but with only minor flow. When the seepage collection canal was drawn down this area of the bank showed signs of instability and continued signs of seepage.

3.3.2 Test Cell 2

At Test Cell No. 2, the bench area between the outside embankment slope and the seepage collection canal was dry, in general. There were a few damp areas around the outside embankment toe of slope. However, no boils were observed on the caprock surface at the outside embankment toe of slope. This indicates that the phreatic line was at or slightly below the level of the caprock during the seepage trial.

4. SEEPAGE MODEL CALIBRATION

4.1 General

A 2 dimensional finite element model of each test cell was constructed in SEEP/W using the as built geometries from the field.

The test cell program was designed to obtain average mass hydraulic conductivity values for each geologic unit, rather than assign specific conductivities to thin bands which could be of limited lateral extent, therefore the foundations were divided into broad geological units within the model. Three layers were used representing the Fort Thompson, Caloosahatchee and Tamiami formations.

4.2 Model

4.2.1 Software

The program SEEP/W by Geo-slope International was used to calibrate the results. SEEP/W is a finite element model rigorously formulated with hydraulic conductivity and water content as a function of pore-water pressure. Steady-state conditions were assumed for the conditions on site on April 23, 2005.

4.2.2 Geometry

SEEP/W is able to analyze both two-dimensional plane and axisymmetric geometry; both options were run to compare how the modeled heads and flows would vary. Two-dimensional geometry is an accurate representation in situations where flow lines are parallel in plan. In situations where flow lines radiate outward from a single point, axisymmetric geometry is more representative.

4.2.3 Boundary Conditions

4.2.3.1 Upstream boundary

The upstream boundary of the model was established as the center of each test cell. Given the flow radially away from this point, a no horizontal flow boundary condition was set.

4.2.3.2 Reservoir

Within the boundary of the reservoir and up the slope of the embankment full reservoir head (20.18 ft elevation for the data set adopted) was applied.

4.2.3.3 Downstream surface

A free surface condition was set for the area downstream of the embankment.

4.2.3.4 Base

A no vertical flow condition was set on the boundary at the base of the model.

4.2.3.5 Downstream boundary

Readings from background piezometers were used to fix the heads at nodes on the downstream boundary of the model.

4.3 Model Parameters

Previous studies have quoted a number of values for the conductivities of the materials in the project area. These values were most recently evaluated and summarized by USACE (Itani and Switanek, 2005), as shown in Table 2.

Given the range of values shown in the table, the values used by USACE 2005 were taken as a suitable starting point for the SEEP/W calibration.

The Test Cell data was reviewed and April 23, 2005 was chosen as a time which fairly represented steady state conditions in the test cells. At that time the water level in the cells was at approximately 12 ft depth. Piezometer readings, and test cell levels did not demonstrate any significant variability. The Figures 3 and 4 below show the information used as a basis for calibration.

4.4 Procedure

Having set up the model grid for each test cell and entered initial values for conductivities, the model was run. Heads from the model results were compared to the known heads at piezometers during the site trials and the flows leaving the cells and entering the canal were compared with field values.

Horizontal and vertical conductivities were then reviewed and adjusted as considered necessary to produce a better correlation, and the model re-run.

This iterative process was repeated until broad agreement was reached between field and model results. Convergence was judged by comparing:

- The total flow leaving the test cells. Error in flow measurements up to 10% was considered possible, therefore agreement to this degree was reasonable.
- The flow lost to background. During the Test Cell program it was not possible to measure flow to background directly. However, for the majority of the test all flow to the cells was taken from the seepage collection canals. When water was taken from an external source (the primary canal), the water level in the seepage collection canal increased. This indicated that a small portion of the flow was lost to background.
- The levels in the piezometers around the test cells. There were sets of six piezometers on each side of each of the test cells. The results from the four sides of each cell were averaged to produce target piezometric values at six points on the model. Given the variation of readings between the four sides of the cells, good agreement was considered to be when the variance between site and model was less than 6 in. Acceptable agreement was considered to be anything less than a foot variance.

4.5 Results

The piezometers were relatively close to the embankment and it was initially felt that flow paths would be parallel in plan, in this region. Plane geometry models were initially used but it was difficult to match the measured results.

Use of axisymmetric geometry, which is applicable to geometries where flow lines diverge in plan, improved the correlation between the test cell data and the model results and results from this geometry are presented here. Eventually agreement was reached with the parameters presented in Table 3. Graphical output from the seepage model using these parameters are shown in Figures 5 and 6.

As a cross check, permeabilities from previous studies were also run in the model for comparison. This was complicated by the fact that the strata have previously been broken into a number of different units. The values used are shown in Table 4.

The figures shown for MODFLOW are the result of preliminary work carried out by Black & Veatch to compare the two programs; this has since been extended as reported in the Groundwater Model Technical Memorandum. The conductivities given are from a preliminary calibration run in MODFLOW. The results in Table 5 show the outcome when the conductivities from these different sources are used as input to SEEP/W.

5. DISCUSSION

The following values represent the best numerical fit calibration to the Test Cell data using the SEEP/W model:

Stratum	k_h (ft/d)	k_v (ft/d)	k_h/k_v
Muck (not modeled)			
Caprock	400	1	400
Fort Thompson	1000	4	250
Caloosahatchee	400	4	100
Tamiami	300	1	300

A 50'x50' hole was deliberately broken through the caprock in the center of each Test Cell to minimize the impact of this, the most variable material in the column, on the calibration. This is considered a realistic situation because:

- It will be necessary to excavate material upstream of the dam to obtain construction materials and therefore break through the caprock.
- The caprock is already broken through in many places around the reservoir and in other places is naturally thin or does not exist.

The results for conductivity above compensate for the hole because the hole was included in the models.

The central caprock hole does mean that seepage loss rates experienced at the Test Cells should not be applied directly for estimating losses from the A-1 Reservoir. The depth of influence from the Test Cells (i.e. the depth to which high water pressure will penetrate) does not match that of the full size reservoir and therefore the hydrological regime is different. The aim of the Test Cells was to derive conductivities representative of the average properties of the relevant geological units.

The conductivity values differ significantly from values used in most recent studies by USACE but are in broadly agreement to values derived from large scale pump tests associated with STA 3/4, Burns & McDonell (2000). In the conclusion to their seepage calibration work Burns & McDonell state: The calibrated ratio of vertical to horizontal hydraulic conductivity was low for each of the layers (on the order of 1:200 to 1:526). This low ratio of vertical to horizontal hydraulic conductivity is likely due to interbedded thin sediment layers with a very low vertical hydraulic conductivity.

In general, horizontal permeabilities are higher and vertical permeabilities are lower than used previously by USACE. USACE (2005) noted that, "Due to the variability of the hydraulic conductivity data available, the hydraulic conductivity values used in the analyses [USACE 2005] were generally based on average values and engineering evaluation and best professional judgment." The USACE 2005 data set included:

- Constant head tests conducted in the area by Ardaman and Associates under USACE contract,
- 12 out of 52 falling head tests located closest to the area of Compartment A test site,
- Additional hydraulic conductivities were extracted from tests conducted by Dames and Moore STA-2 area, and
- MWH's seepage model of the area.

The following quotes from "Groundwater Hydrology", Second Edition, 1980 explain some of the concerns with this type of data:

- "Permeameter (constant head or falling head) results may bear little relation to actual field hydraulic conductivities. Undisturbed samples of unconsolidated material are difficult to obtain, while disturbed samples experience changes in porosity, packing, and grain orientation, which modify hydraulic conductivities. Then, too, one or even several samples from an aquifer may not represent the overall hydraulic conductivity of an aquifer. Variations of several orders of magnitude frequently occur for different depths and locations in an aquifer. Furthermore, directional properties of hydraulic conductivity may not be recognized." (page 74)
- "Ratios of Kh/Kv usually fall in the range of 2 to 10 for alluvium, but values up to 100 or more occur where clay layers are present." (page 81)

Fell et al (1992) state the ratios of Kh/Kv greater that 100 "are not uncommon" in natural deposits.

Some of the Kh/Kv values from the SEEP/W calibration of the test cell results are higher than 100. This may be a result of the contrast between relatively impermeable limestone stringers which have been identified in boreholes, and highly permeable shell beds which have also been witnessed at the Test Cell site. Such variation is evident from the conductivity values presented in Table 1. The Test Cell results are:

- Free of the effects of disturbance in samples,
- Test enormous volumes of soil compared to a standard permeability test, and
- Were carried out within the reservoir site.

The Test Cell program is the second (after STA 3/4) large scale test of these materials in-situ which has concluded that a high horizontal to vertical permeability ratio is appropriate.

The parameters derived in this Technical Memorandum should be refined and modified as considered necessary to optimise the match between MODFLOW calibration, SEEP/W calibration, Test Cell results, other relevant conductivity testing data and engineering judgment.

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TABLES

Table 1 Approximate Ranges of Hydraulic Conductivity of Materials that Compose the Surficial Aquifer System, Broward County

Geologic formation: **Qa**, Anastasia Formation; **Qf**, Fort Thompson Formation; **Qk**, Key Largo Limestone; **Qm**, Miami Oolite; **Qp**, Pamlico Sand; **Th**, Hawthorn Formation; **Tt**, Tamiami Formation; **Tth**, undifferentiated Tamiami Formation or Hawthorn Formation; **Ttl**, Tamiami Formation, lower part; **Ttu**, Tamiami Formation, upper part.

Horizontal hydraulic conductivity		**Materials - Lithology and Porosity**	**Geologic Formations**
Qualitative Permeability	**Range (ft/d)**		
Very high	≥1,000	Solution-riddled limestone, commonly shelly or sandy.	Qf, Qa
		Calcareous sandstone, may be shelly or have shell fragments; solution holes or rib-like channels.	Qa, Tt
		Coralline limestone, reefal, very porous.	Qk
High	100-1,000	Gray, shelly limestone, locally sandy, relatively soft.	Tt
		Limestone or calcareous sandstone interbedded with sand, or with sand partially filling cavities.	Qa, Tt, Qf
		Coarse shell sand and quartz sand.	Tt
		Dense, charcoal gray to tan limestone with some solution channels, usually shelly or sandy.	Ttu
Moderate	10-100	Very fine to medium, relatively clean quartz sand.	Qp, Qa, Tt
		Fine to medium quartz and carbonate sand.	Tt
		Cream-colored limestone with minor channels.	Qf, Qa
		Tan, cream, or greenish limestone, locally containing shell sand.	Tt
		Calcareous sandstone and sand.	Tt, Qa
		Slightly clayey or sandy, gray limestone	Tt
		Oolitic limestone.	Qm
Low	0.1-10	Very fine to medium sand with some clay, silt, or lime mud, locally shelly.	Tt, Qf, Qa
		Soft gray or buff limestone with silt and fine sand.	Tt
		Dense, calcareous sandstone.	Tt
		Light-green, fine-grained foraminiferal limestone with very fine quartz sand.	Tt
		Dense, hard limestone with very small cavities or channels; approximately equal mixtures of sand, shell fragments, and lime mud.	Qf

<table>
<tr><td colspan="4">Geologic formation: Qa, Anastasia Formation; Qf, Fort Thompson Formation; Qk, Key Largo Limestone; Qm, Miami Oolite; Qp, Pamlico Sand; Th, Hawthorn Formation; Tt, Tamiami Formation; Tth, undifferentiated Tamiami Formation or Hawthorn Formation; Ttl, Tamiami Formation, lower part; Ttu, Tamiami Formation, upper part.</td></tr>
<tr><th colspan="2">Horizontal hydraulic conductivity</th><th rowspan="2">Materials - Lithology and Porosity</th><th rowspan="2">Geologic Formations</th></tr>
<tr><th>Qualitative Permeability</th><th>Range (ft/d)</th></tr>
<tr><td rowspan="3">Very low to practically impermeable.</td><td rowspan="3">≤.01</td><td>Green clay or silt; locally with very fine sand.</td><td>Th, Tth, Ttl, Ttu,</td></tr>
<tr><td>Sandy, shelly lime mud.</td><td>Tt</td></tr>
<tr><td>Very dense, hard limestone with no apparent solution cavities or fractures.</td><td>Qf</td></tr>
</table>

(USGS, WRI report 87-4034).

Table 2 Range of Conductivities Taken in Previous Studies

Stratum	Source	Kh (ft/d)	Kv (ft/d)	kh/kv
Muck (not modeled)	MIKE SHE 2004	30	28	1.07
	Levee High 2004 (MWH)	54	0.68	79.41
	USACE 2004	30	5	6.00
	quoted by USACE 2005	0.15	6.8	0.02
	quoted by USACE 2005	0.5	0.25	2.00
	quoted by USACE 2005	22	11	2.00
	USACE design value 2005	40	9	4.44
Caprock	STA 3/4	100	0.5	200.00
	MIKE SHE 2004	30	3	10.00
	Levee High 2004 (MWH)	0.3	3	0.10
	USACE 2004	10	1	10.00
	quoted by USACE 2005	5	5	1.00
	quoted by USACE 2005	135	1.35	100.00
	quoted by USACE 2005	54	27	2.00
	quoted by USACE 2005	117	1.17	100.00
	USACE design value 2005	100	10	10.00
Ft Thompson (7-23ft)	STA 3/4	200	0.38	526.32
	MIKE SHE 2004	11	1	11.00
	Levee High 2004 (MWH)	285	1.4	203.57
	USACE 2004	60	25	2.40
	quoted by USACE 2005	35	23	1.52
	quoted by USACE 2005	60	30	2.00
	quoted by USACE 2005	22	11	2.00
	USACE design value 2005	60	25	2.40
Ft Thompson (23-34ft)	STA 3/4	200	0.38	526.32
	MIKE SHE 2004	11	1	11.00
	Levee High 2004 (MWH)	285	1.4	203.57
	USACE 2004	60	25	2.40

Stratum	Source	Kh (ft/d)	Kv (ft/d)	kh/kv
	quoted by USACE 2005	150	23	6.52
	quoted by USACE 2005	350	30	11.67
	quoted by USACE 2005	28.3	11	2.57
	quoted by USACE 2005	100	50	2.00
	USACE design value 2005	200	75	2.67
Caloosahatchee	STA 3/4	420	1.3	323.08
	MIKE SHE 2004	60	6	10.00
	Levee High 2004 (MWH)	350	1.4	250.00
	USACE 2004	250	125	2.00
	quoted by USACE 2005	4.07	2.07	1.97
	quoted by USACE 2005	8.4	4.2	2.00
	USACE design value 2005	250	125	2.00
Tamiami	MIKE SHE 2004	570	57	10.00
	Levee High 2004 (MWH)	36	18	2.00
	quoted by USACE 2005	1.76	1.76	1.00
	quoted by USACE 2005	6.99	6.99	1.00
	quoted by USACE 2005	3.78	3.78	1.00
	USACE design value 2005	36	18	2.00

NOTE: sources quoted by USACE 2005 include:

testing by Ardaman and Associates
testing by Nodarse Associates
testing at Compartment A
Dames and Moore testing at STA-2
MWH model
DHI model

Table 3 Conductivity Parameters

Stratum	k_h (ft/d)	k_v (ft/d)	k_v/k_h
Muck (not modeled)			
Caprock	400	1	0.0025
Fort Thompson	1000	4	0.004
Caloosahatchee	400	4	0.01
Tamiami	300	1	0.0033

Table 4 Comparison with Other Studies

	Kh / Kv (ft/d)			
Models	Caprock	Ft Thompson	Caloosahatchee	Tamiami
SEEP/W	400 / 1	1000 / 4	400 / 4	300 / 1
MODFLOW	100 / 2.5	400 / 15	1000 / 4	400 /1
USACE 2005	100 / 10	7-23 ft 60/25*	250/ 125	36 / 18
		23-34 ft 200/75		
USACE 2004	10 / 1	7-23 ft 60/25	90 / 45**	36 / 18
		23-34 ft 160 / 40*		

* Previously split into two layers.

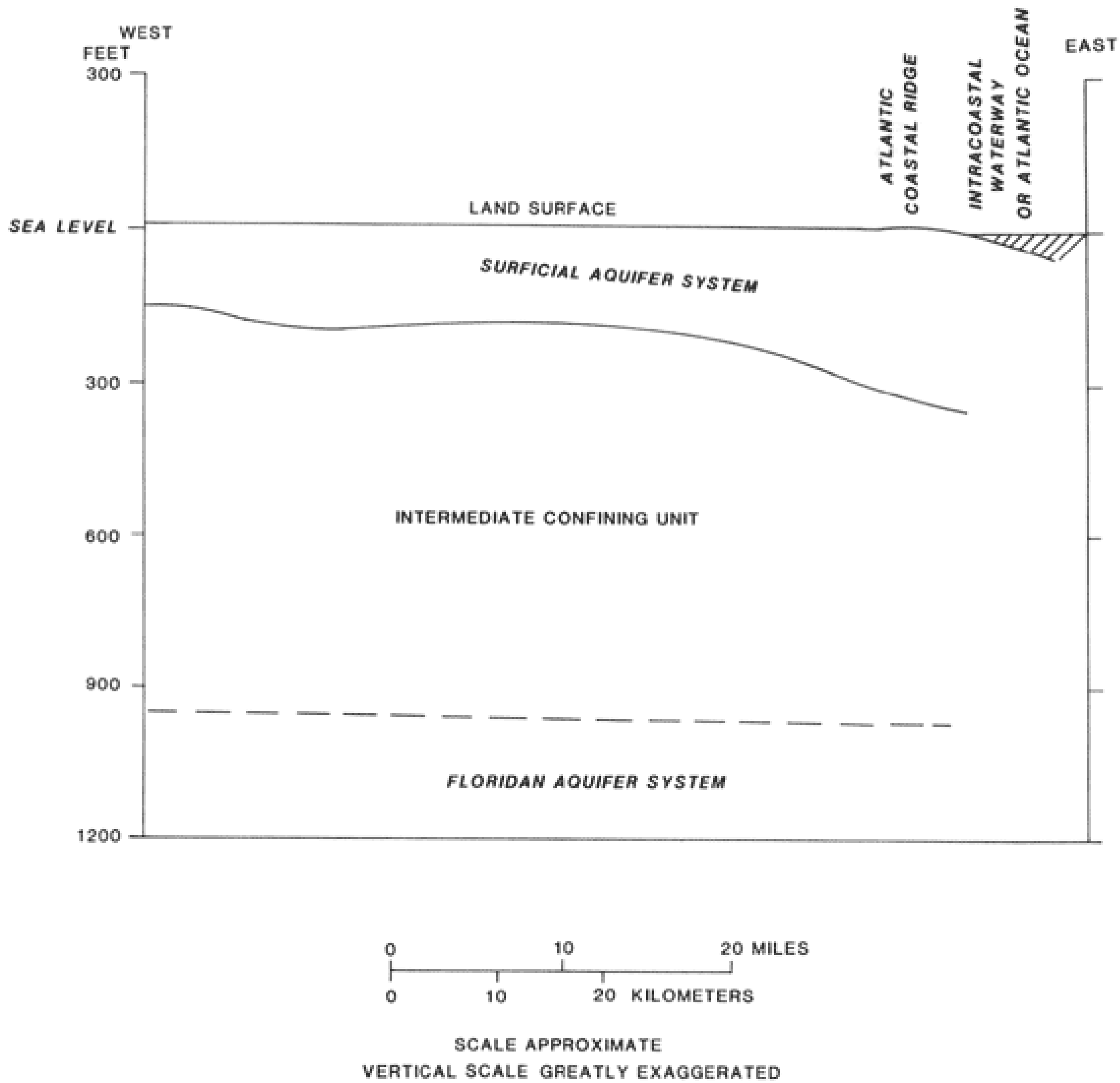
** Designated Lower Okeechobee/Ft. Thompson by USACE 2004.

Table 5 Comparison of Outputs Compared to Measured Data Using Parameters from Other Studies

			Piezometers (total head ft)						Flow (cu ft/hr)	
	Models		2A	2B	2C	3A	3B	3C	Total	Lost
Cell 1		Target values	**8.61**	**7.71**	**6.90**	**7.38**	**7.02**	**6.83**	**4979**	
	SEEP/W	Model result	7.66	7.10	6.65	6.76	6.85	6.63	4772	48
		difference (in)	-11	-7	-3	-7	-2	-2	-4%	1%
	MODFLOW	Model result	8.55	7.69	6.93	7.02	7.40	6.91	5243	472
		difference (in)	-1	0	0	-4	5	1	5%	9%
	USACE 2005	Model result	10.33	10.08	9.74	7.59	7.42	7.60	6080	39
		difference (in)	21	28	34	3	5	9	22%	1%
	USACE 2004	Model result	8.00	7.93	7.83	7.11	7.11	7.14	3952	104
		difference (in)	-7	3	11	-3	1	4	-21%	3%
Cell 2		Target values	**7.28**	**7.17**	**6.79**	**6.72**	**6.70**	**6.71**	**2394**	
	SEEP/W	Model result	6.92	7.35	6.74	6.44	6.96	6.71	2483	7
		difference (in)	-4	2	-1	-3	3	0	4%	0
	MODFLOW	Model result	7.72	7.62	6.92	6.68	7.32	6.89	4397	440
		difference (in)	5	5	2	0	7	2	84%	10%
	USACE 2005	Model result	9.37	9.38	9.45	6.99	7.13	7.46	5526	53
		difference (in)	25	27	32	3	5	9	131%	1%
	USACE 2004	Model result	7.33	7.33	7.33	6.68	6.79	6.86	2760	11
		difference (in)	1	2	6	0	1	2	15%	0

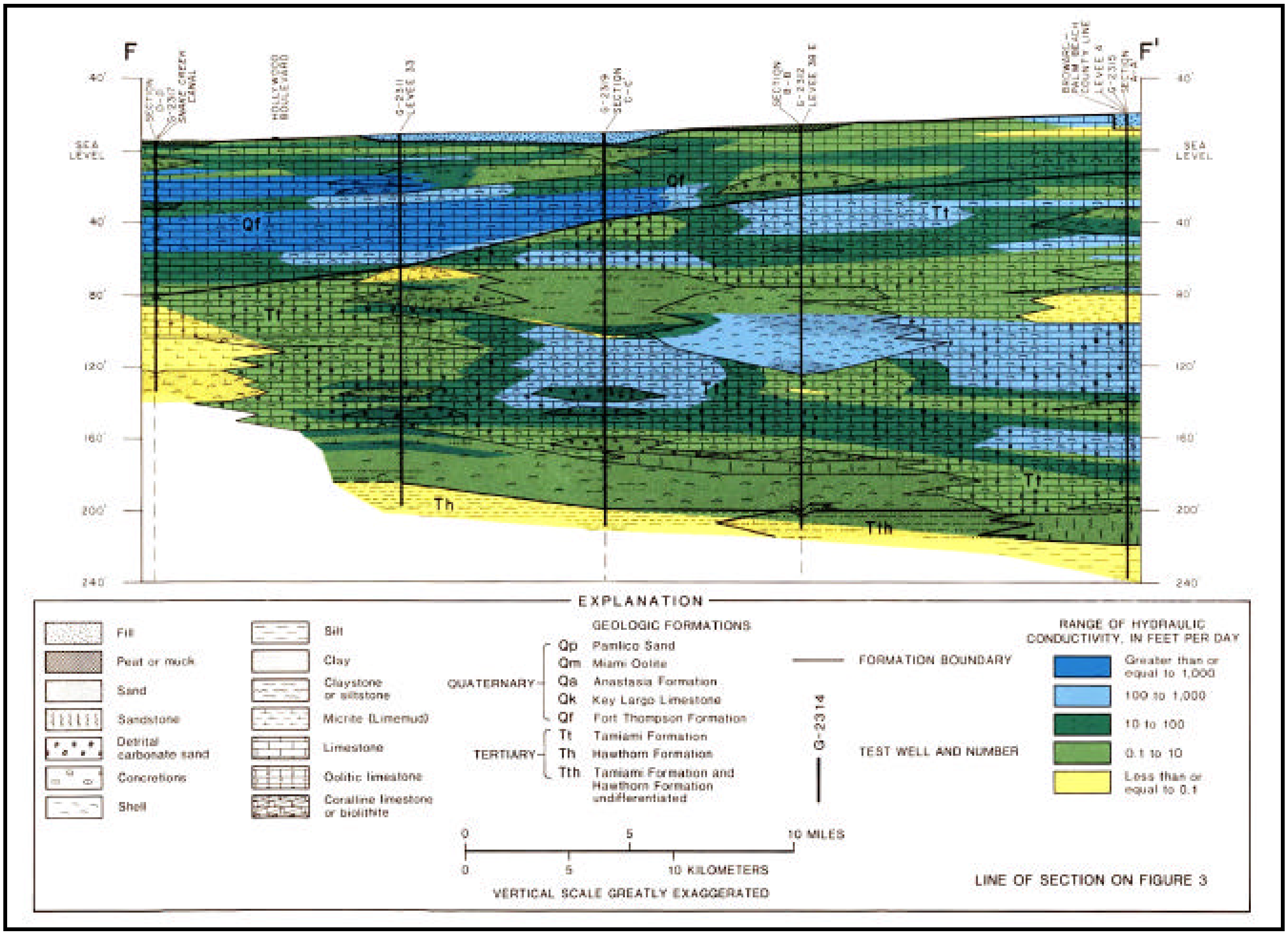
FIGURES

Figure 1 Schematic Hydrogeological Framework



(Fish, 1987)

Figure 2 Variability in the Surficial Aquifer System, Broward County



(USGS, WRI report 87-4034)

Figure 3 Test Cell 1 Conditions on 23 April 2005 Used in Model Calibration

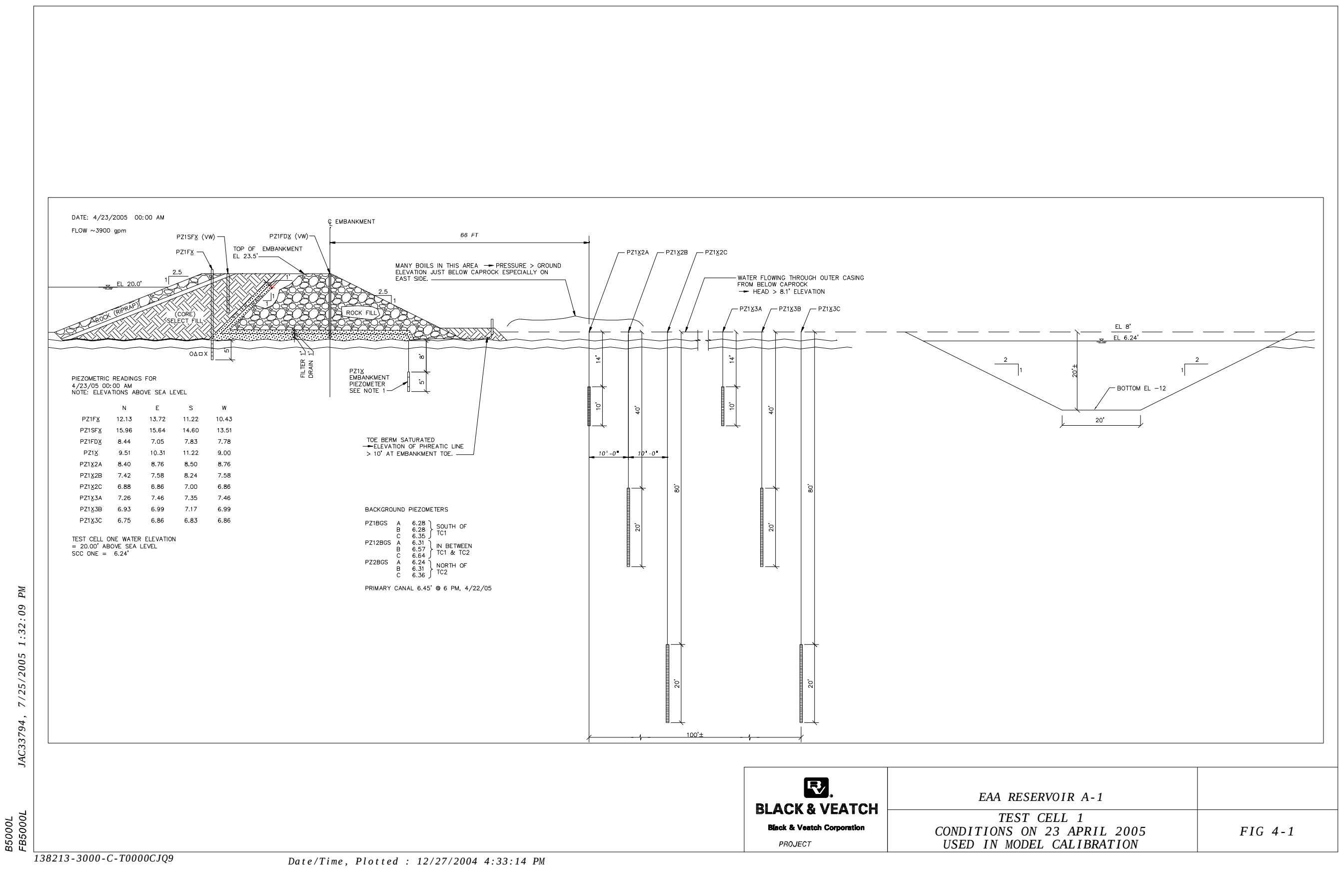


Figure 4 Test Cell 2 Conditions on 23 April 2005 Used in Model Calibration

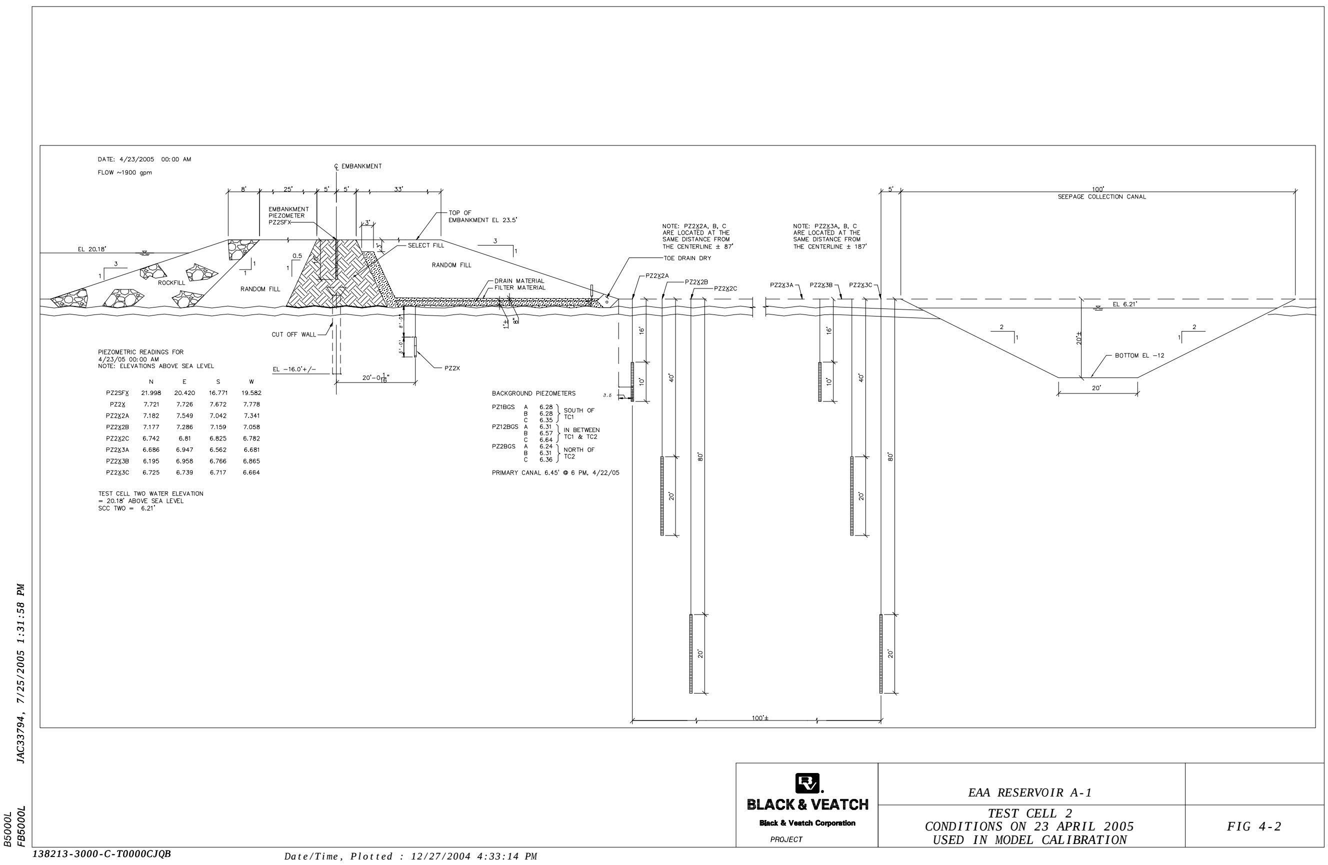


Figure 5 SEEP/W Output - Test Cell 1 Flow Lines and Pressure Contours Using Best Fit Parameters

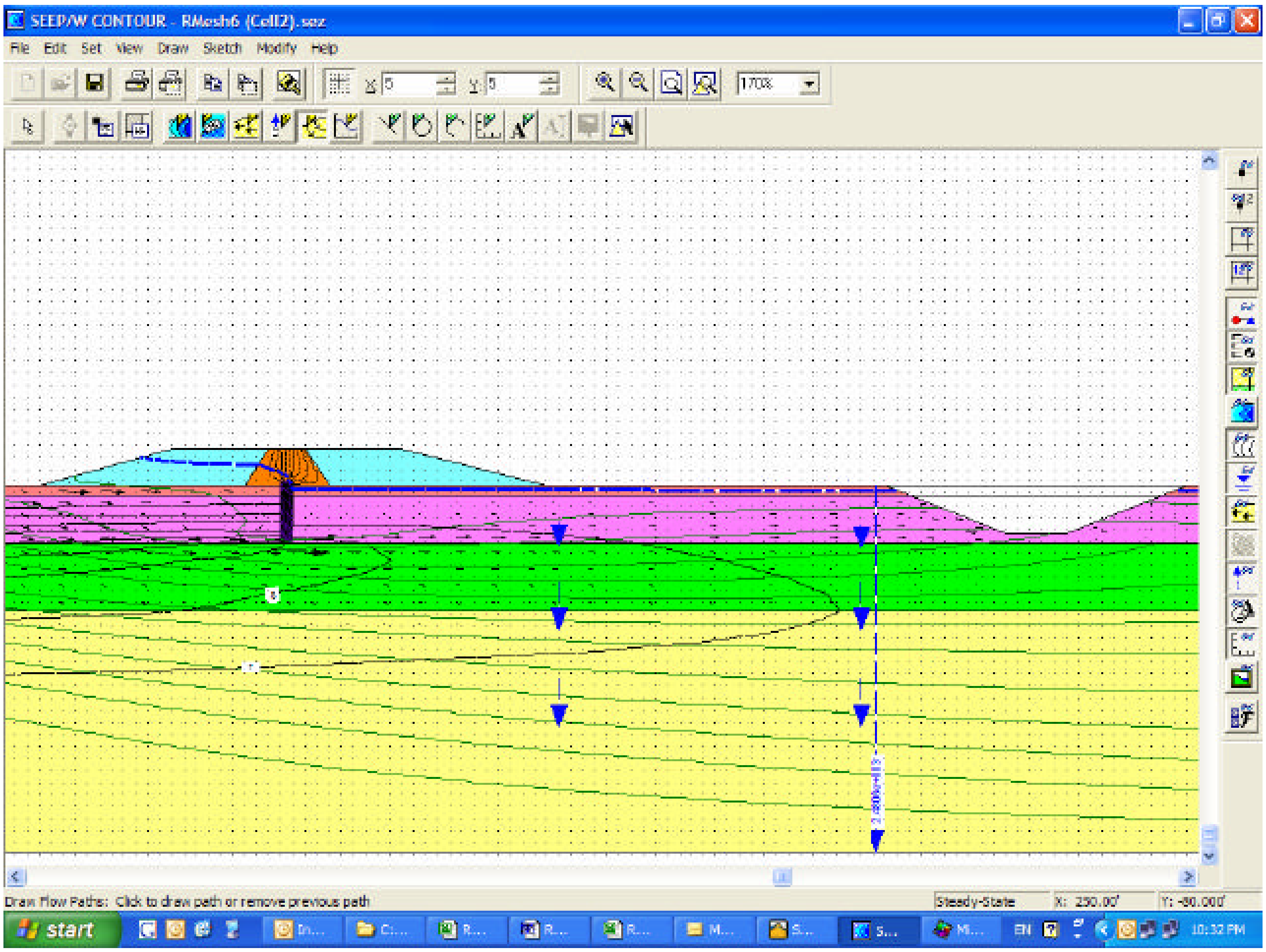


Figure 6 SEEP/W output - Test Cell 2 flow lines and Pressure Contours Using Best Fit Parameters